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Pacific Science (2000), vol. 54, no. 1: 31–38

Distribution, Recruitment, and Growth of the Black-Lip Pearl Oyster, *Pinctada margaritifera,* in Kāne'ohe Bay, O'ahu, Hawai'i[1]

S. Ku'ulei Rodgers,[2] Neil A. Sims,[3] Dale J. Sarver,[3] and Evelyn F. Cox[2]

ABSTRACT: Stocks of Hawaiian black-lip pearl oysters, *Pinctada margaritifera* (Linnaeus, 1758), appear to have been depleted by overfishing and environmental degradation. Permanent survey transect sites were set up in Kāne'ohe Bay in 1989 to monitor changes in the status of stocks. Only 17 pearl oysters were found in 1989. Transects were resurveyed in 1997, and 22 pearl oysters were counted. Most were found on the slopes of patch reefs around the Sampan Channel in 2–6 m depth. Recruitment is low. Standing stock estimated from observed densities on transects in 1997 and the extent of available habitat is about 950 individuals. The size distribution of pearl oysters on transects indicates that they are fished, despite legal protection. Growth of *Pinctada margaritifera* in Kāne'ohe Bay is comparable with that in other locations. The prospects for commercial culture of black pearls in Kāne'ohe Bay are limited by environmental constraints and the heavy recreational use of the bay.

The black-lip pearl oyster, *Pinctada margaritifera* (Linnaeus, 1758), occurs throughout the tropical Indo-West Pacific. It is uncommon around the main islands of Hawai'i (Kay 1979) and is distributed throughout the Northwestern Hawaiian Islands as far as Midway Island (Galtsoff 1933). Small numbers of *P. margaritifera* were reported from "one of the coral reefs" in Kāne'ohe Bay, O'ahu (Galtsoff 1933:6). Galtstoff (1933) described good growth and survival rates for 310 oysters introduced to Kāne'ohe Bay from Pearl and Hermes Reef in 1930.

Stocks of *P. margaritifera* have long been exploited for the value of the nacreous mother-of-pearl shell. Pearl oysters were harvested in Pearl Harbor, O'ahu, for King Kamehameha during the late 1700s and early 1800s (Kay 1979). A commercial fishery operated at Pearl and Hermes Reef in the Northwestern Hawaiian Islands from 1927 to 1929 and yielded around 100 tons of shell. Stocks were, however, quickly depleted (Galtsoff 1933) and have not since recovered (Kay 1979). Interest in black pearl culture has increased throughout the Pacific, with expanding commercial developments in French Polynesia, the Cook Islands, Okinawa, and Fiji. The industry in French Polynesia currently generates more than US$150 million annually.

This study surveyed permanent transects in 1989 and 1997 in Kāne'ohe Bay to monitor changes in abundance and distribution of *P. margaritifera.* Spat grow-out trials at Moku o Lo'e in Kāne'ohe Bay provided information on growth rates. Recruitment was also monitored at four sites in Kāne'ohe Bay. The potential for development of the resource, through enhancement of wild stocks and artificial culture trials, was also assessed.

Study Site

Kāne'ohe Bay is located on the northeastern coast of the island of O'ahu (Figure 1). It is the largest embayment in the state of Hawai'i (Smith et al. 1973) and the most extensively studied (Bathen 1968, Smith et al. 1981, Laws and Allen 1996). It extends ap-

[1] Research was funded by an internship to S.K.R. from the State of Hawai'i Department of Land and Natural Resources and the Sea Grant Program at the University of Hawai'i. Manuscript accepted 7 May 1999.

[2] Hawai'i Institute of Marine Biology, P.O. Box 1346, Coconut Island, Kāne'ohe, Hawai'i 96744.

[3] Black Pearls, Inc., P.O. Box 525, Hōlualoa, Hawai'i 96725.

FIGURE 1. Map of Kāne'ohe Bay, O'ahu, Hawai'i, showing 1989 and 1997 transect and recruitment study sites. Sites surveyed in 1989 and 1997 are shown as circles (open circles, *Pinctada margaritifera* absent; solid circles, *P. margaritifera* present). Squares are sites surveyed only in 1997 (open squares, *P. margaritifera* absent; solid squares, *P. margaritifera* present). Solid triangles are recruitment sites.

proximately 13 km in length and 4.5 km in width. Two navigable channels penetrate the outer barrier reef, at the northern and southern ends of the bay. The inshore, inner bay, and outer bay compose the major physiographic zones. The inshore zone comprises the intertidal zone and the fringing reef. The lagoon and the patch reefs compose the inner bay. The lagoon is divided into three sectors: South Bay, Central Basin, and North Bay. The outer bay zone includes a barrier reef (Smith et al. 1973). Seawater is driven shoreward across the barrier reef by wave action. Prevailing tradewinds blow from the northeast and east approximately 70% of the time. Circulation in the inner bay is determined by bathymetry and driven by tides and wind and the inflow across the barrier reef (Bathen 1968). The South Bay has more restricted circulation.

Anthropogenic influences include runoff of sediments, dredging, channelization of streams, changes in the watershed and riparian environments, 25 yr of sewage effluent discharge, and introductions of invasive species. Despite an increase in the human population, the water quality of Kāne'ohe Bay has improved following sewage diversion in 1978 (Laws and Allen 1996).

Kāne'ohe Bay is an ideal location for survey of the distribution of *P. margaritifera.* It is one of the few areas in the state where a relatively substantial population remains. Environmental records exist for physical parameters, topography, and bathymetry within the bay and the surrounding watershed because of extensive scientific research on the ecosystem (Bathen 1968, Smith et al. 1973, 1981, Hunter 1993, Laws and Allen 1996).

MATERIALS AND METHODS

Distribution and Abundance

The 1989 survey concentrated on patch reefs identified by local informants (Lester Zukeran, pers. comm.), with 17 patch reef and four barrier reef sites (Figure 1). Other sites were added in 1997 to examine the extent of pearl oyster distribution throughout the bay, including nine sites on the fringing reef and nine on the barrier reef (Figure 1). Areas surveyed at each site ranged from 200 to 1000 m^2.

Standard line transects of 20 to 100 m length (depending on the size of the patch reef and suitable substrate) were laid along the crest or slope of patch reefs. Divers searched 5 m to each side. The depths varied, depending on the slope of the reef: barrier reef flat sites were typically at 0–2 m depth, and transects along fringing, patch, and barrier reef slope sites ranged from 7 to 8 m depth. No suitable substrate for *P. margaritifera* was found below 8 m, where fine silt dominates.

Initial measurements in 1989 included dorsoventral measurement (DVM, shell diameter from the umbo to the outermost continuous edge of the nonnacreous border excluding the digitate growth processes) and heel depth (dorsal edge of the hinge to the deepest point of the valves) when the oyster was accessible. Only DVM was measured in 1997.

The total number of oysters was extrapolated using estimates of total area of reef types from Hunter (1993), and density estimates were calculated separately for each of the three bay sectors. Total numbers for the barrier reef were estimated from Hunter's (1993) barrier reef flat and slope areas.

Recruitment

One site within each zone of the bay was chosen to monitor recruitment (Figure 1). Recruitment was estimated using spat collecting techniques from French Polynesia and the Cook Islands (Cabral et al. 1985). Spat collectors were 85 by 35 cm bags of 1.5-mm mesh, loosely filled with a 1-m^2 piece of 70% shade cloth. At each sampling station, 10 bags were placed at a depth of 8 m, anchored to the substrate, and suspended approximately 1 m above the substrate by internal flotation. Bags were deployed for 3 months. To assess seasonal variation, two collection periods were sampled: April to June 1997

TABLE 1

ESTIMATED POPULATION SIZE OF *Pinctada margaritifera* IN KĀNE'OHE BAY IN 1997 BASED ON TOTAL REEF SLOPE AREAS (FROM HUNTER 1993) AND AVERAGE DENSITY DETERMINED FROM FIELD TRANSECTS

REEF TYPE	LOCATION	REEF SLOPE AREA (m^2)	DENSITY PER 100 m^2	ESTIMATED NO. OYSTERS
Patch reef	South Bay	21,171	0	0
	Central Basin	256,975	0.28	728
	North Bay	166,452	0.08	133
Subtotal				861
Barrier reef	Reef slope	82,000	0.06	48
	Reef flat	5,859,225	0	0
Subtotal				48
Fringing reef	South Bay	41,868	0	0
	Central Basin	122,027	0.03	41
	North Bay	109,315	0	0
Subtotal				41
Grand total				950

and July to September 1997 to coincide with natural spawning times. An adult population is maintained on longlines at Moku o Lo'e (Figure 1), therefore recruitment at that site was assessed over a longer period of time, with collectors deployed from longlines for 8 months commencing in August 1995, October 1995, January 1996, and April 1996. In addition, spat collection bags were suspended from the substrate concurrent with the 1997 sampling periods throughout the bay.

Growth

Nursery grow-outs of spat acquired from laboratory-spawned oysters initially occurred in seawater tanks on Moku o Lo'e. Grow-out continued on longlines after spat reached between 10 and 15 mm. Spat initially numbered in the thousands, and juvenile individuals were not identified. Measurements were obtained from two age groups, juveniles (DVM < 116 mm) and adults (DVM > 116 mm). Growth estimates were based on mean DVM of five individuals from each of five culture panels for adults and mean DVM of seven to eight measurements from each of four grow-out baskets. Adults ranged from 116 to 154 mm at the start of the trials. Juveniles ranged from 19 to 64 mm at the start of the trials. Growth was monitored monthly for 18 months.

RESULTS

In 1989, only 17 pearl oysters were found at seven sites (33% of the sites sampled), with an average density of 0.13 per 100 m^2. In 1997, 22 pearl oysters were found at nine of the sites surveyed in 1989 (43% of the sites sampled), with an average density of 0.18 per 100 m^2 (Table 1). Only one pearl oyster was found on the fringing reef and seven on the barrier reef (Table 2). Although the number of oysters increased by 29% from 1989 to 1997, the increase was primarily due to a profusion of oysters at site 20 (Central Basin) in 1997 (10 individuals), where none was recorded in 1989.

In 1997 no oysters were found in the South Bay, mean density in the Central Basin was 0.2 per 100 m^2, and 0.04 per 100 m^2 in the North Bay. Overall abundance on the patch reefs was estimated at 861 individuals (Table 1), with 85% in the Central Basin in close proximity to the Sampan Channel. Estimated numbers of oysters on the fringing reef and barrier reef were 41 and 48, respectively (Table 1). Highest density occurred in the Central Basin on both the fringing and barrier reefs. Standing stock in Kāne'ohe Bay totaled 950 pearl oysters. Using 95% estimated confidence limits for the mean density overall, we estimated that the density in the bay could be as low as 384 or as high as 1538 pearl oysters.

TABLE 2

ABUNDANCE OF *Pinctada margaritifera* IN KĀNE'OHE BAY (TRANSECTS ARE LISTED BY REEF TYPE AND LOCATION)

REEF TYPE	LOCATION	TRANSECT NO.	AREA (m^2)	NO. OF OYSTERS	
				1989[a]	1997
Patch reef	South Bay	11	200	0	0
		12	500	0	0
	Central Basin	1	1,000	3	0
		3	1,000	4	0
		10	500	0	0
		14	500	2	3
		15	500	1	0
		16	500	0	1
		17	500	0	0
		18	500	0	0
		19	500	2	1
		20	500	0	10
	North Bay	5	500	0	0
		6	500	0	0
		7	500	0	1
		8	500	0	0
		9	500	0	1
Barrier reef	South Bay	22	1,000	ND	0
		23	1,000	ND	0
		24	1,000	ND	0
	Central Basin	2	1,000	0	0
		4	1,000	4	2
		13	500	0	2
		21	500	1	1
		25	1,000	ND	2
		26	1,000	ND	0
		27	1,000	ND	0
	North Bay	28	1,000	ND	0
		29	1,000	ND	0
		30	1,000	ND	0
Fringing reef	South Bay	31	1,000	ND	0
		32	1,000	ND	0
		33	1,000	ND	0
	Central Basin	34	1,000	ND	0
		35	1,000	ND	1
		36	1,000	ND	0
	North Bay	37	1,000	ND	0
		38	1,000	ND	0
		39	1,000	ND	0

[a]ND indicates no data because these transects were not surveyed in 1989.

Pinctada margaritifera recruits were not found in spat collection bags during any recruitment period. Recruits of a congener, *Pinctada radiata,* were collected; the predator *Stylocus* sp. (Platyhelminthes) was found at all four sites within spat collection bags; and the molluscivore *Cymatium* sp. was found at the North Bay site.

Shell diameters for pearl oysters on the transects ranged from 80 to 215 mm in 1989 and from 35 to 230 mm in 1997 (Figure 2). Although mean DVM increased between surveys from 148 mm in 1989 to 174 mm in 1997, size distributions for the 2 yr were not significantly different (Kolmogorov-Smirnov test, $P = 0.46$).

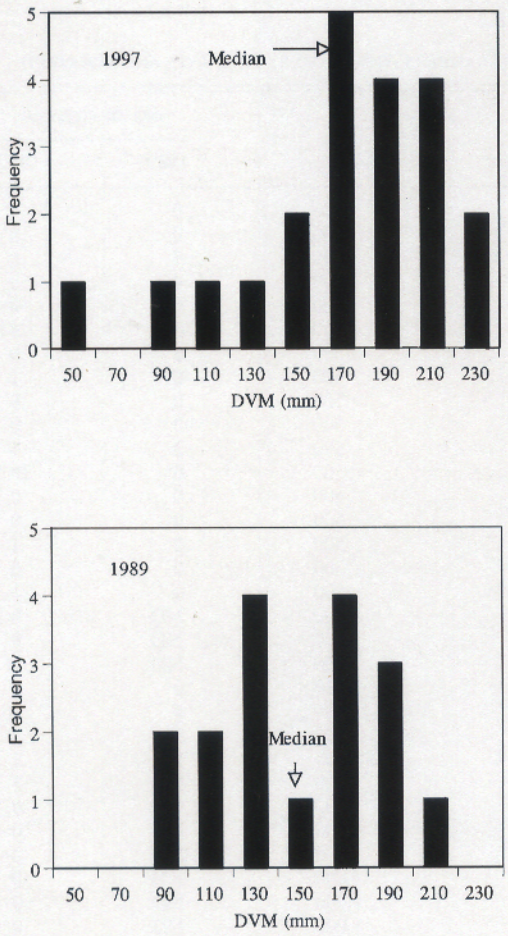

FIGURE 2. Size frequency diagram for *Pinctada margaritifera* in Kāne'ohe Bay. Sample size in 1989, $n = 17$; in 1997, $n = 22$.

Growth rates varied widely between individual adult *P. margaritifera,* with wide fluctuations in shell increments over successive intervals. Some individuals occasionally showed a reduction in shell size, because the outer periostracal margin was broken back or sloughed off (Sims 1988). Monthly mean growth estimates ranged from −38 mm per year to 59 mm per year, with a mean DVM increase of 8.7 (SD = 2.5) mm per year. For juveniles, growth averaged 52.6 (SD = 5.2) mm per year.

DISCUSSION

The population of *P. margaritifera* in Kāne'ohe Bay is restricted in size and distribution. Pearl oysters were most abundant between 2 and 6 m depth close to the Sampan Channel in the Central Basin. *Pinctada margaritifera* settles prolifically in shallow water elsewhere (Coeroli et al. 1983, Cabral et al. 1985), but wave action and/or freshwater runoff may hinder survival in shallow water in Kāne'ohe Bay. Pearl oysters do not survive well in fine silts (Sims 1990), and the presence of silt in Kāne'ohe Bay may prevent oyster settlement in the South Bay. Strong waves may restrict pearl oysters from settlement in the North Bay.

Subsequent observations (S.K.R., pers. obs.; S. P. Kolinski, pers. obs.) have found several clusters of oysters at 10 m depth close to the Sampan Channel. We suspect that these aggregations are from divers gathering and sequestering the oysters. The rapid proliferation of oysters at site 20 (Central Basin) should therefore be viewed as an anomaly, perhaps linked to human interference.

No recruitment of pearl oysters was found during this study. Although a reproductively active population of between 40 and 60 adult *P. margaritifera* was maintained at Moku o Lo'e during the period of spat collection, only recruits of its congener, *P. radiata,* were found during a year of monitoring at that site. Absence of *P. margaritifera* on collection bags may be due to limited sampling, the small breeding population within the bay, predation, or larval transport from the bay.

Apparently over half of the oysters found on the 1997 transects have recruited since the original 1989 survey. All oysters on the baseline survey in 1989 should have reached the maximum size (230 mm) by 1997 if they had survived. Lifespan can exceed 30 yr (Reed 1973). Therefore either mortality occurred between surveys, including individuals in the maximum size class, or large adults were being removed from the population. Small individuals on transects indicates some recruitment in Kāne'ohe Bay; however, the low numbers suggest that little recruitment has occurred since 1989.

At Kāne'ohe Bay, land-based grow-out increased survival of young spat in the nursery, but growth rates were slow compared with growth rates of spat in the ocean. Growth rates for juveniles placed on the longlines were comparable with or higher than those at sites in the South Pacific (Sims 1994). Refinements in filtration techniques, flow-rate parameters, or changes in oyster densities in the nursery could improve growth rates of land-based spat.

Expansion of the black pearl industry across the Pacific is constrained by environmental limits to stock abundance or previous histories of overfishing. The pearl oysters in Kāne'ohe Bay and Pearl and Hermes Reef reflect these respective limitations. Priorities for *P. margaritifera* center on enhancement of natural populations and supply of stock to pearl farms through spat collectors or hatchery developments (Sims 1988). Standing stock in Kāne'ohe Bay is sufficient for use in small-scale hatchery trials, but commercial hatcheries would need other brood stock sources to prevent possible founder effects. The limited distribution and narrow depth range of *P. margaritifera* reflect the suboptimal conditions for this species in the bay. The potential for wild stock enhancement or commercial culture of pearl oysters in the bay is therefore unlikely. Any proposed commercial venture must also compete with various recreational interests in the bay and address the security concerns involved with pearl farming in heavily utilized waters. Although growth rates of *P. margaritifera* in the bay indicate that pearl farming would be technically feasible, the heavy recreational use makes it practically impossible.

Pinctada margaritifera is a protected marine fisheries resource. It is illegal to take, kill, possess, remove, or sell this species in Hawai'i without a permit. The black-lip pearl oyster was a vital part of the native culture (Summers 1990). Continued legal protection is vital to this species.

CONCLUSIONS

Kāne'ohe Bay is one of the richest habitats in Hawai'i for this rare species, yet only about 950 individuals remain in the bay. The population appears to be maintaining itself at a low density. Oysters are most abundant in the Central Basin where high water quality and good water circulation occur. Recruitment is very low throughout the bay. The limited distribution of *P. margaritifera* in the Central Basin and its narrow depth range may increase susceptibility to environmental stresses, catastrophic events, or anthropogenic activities. Kāne'ohe Bay has conditions favorable to growth of *P. margaritifera,* and growth rates in the bay are comparable with those in other locations.

The effects of environmental, demographic, and genetic stochasticity can be dramatic in small populations. Protection is critical to maintain an effective population size. Initial recovery may be slow in a long-lived species. A combination of low reproductive rates, due to a small population size, and low recruitment may hinder restocking efforts for depleted populations.

ACKNOWLEDGMENTS

We thank Sherwood Maynard and Paul Jokiel for their support. This is contribution no. 1049, Hawai'i Institute of Marine Biology.

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